Ostracode faunal changes after the mid-Neogene climatic optimum elucidated in the Middle Miocene Kobana Formation, Central Japan

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Abstract. One hundred and forty-nine ostracode species are identified among 42 samples from the lower to middle part of the Middle Miocene Kobana Formation, Arakawa Group, distributed in Tochigi Prefecture, Central Japan. Dominant throughout the formation are such species living around Japan as *Schizocythere kishinouyei* (Kajiyama), *Paracytheridea neolongicaudata* Ishizaki, *Cornucoquimba moniwensis* (Ishizaki), *Cornucoquimba saitoi* (Ishizaki) and *Cythere omotenipponica* Hanai. Tropical to warm-temperate species living off Southwest Japan are abundant, but circumpolar and cryophilic species are also present (less than 10%) in most samples. Q-mode cluster and principal components analyses disclose the following sequence of ostracode faunas : 1) The lowest part is dominated by nearshore and subtropical species and contains about 5-13% of circumpolar and cryophilic species ; 2) The lower middle part is dominated by lower sublittoral to upper bathyal muddy dwellers, suggesting a rapid increase of water depth. The horizon characterized by the increase of deep cool-water species is recognized ; 3) The middle to upper part, characterized by lower to middle sublittoral subtropical to warm-temperate water species mixed with intertidal to upper sublittoral ones ; 4) The upper part containing many *Laperousecythere* species, suggesting a cooler climate. Analyses of ostracode faunas indicate that after the mid-Neogene climatic optimum, benthic environments underwent fluctuations of water temperatures, with no rapid decrease, in the Karasuyama area.

Key words : Central Japan, Kobana Formation, Middle Miocene, Miocene isotope, Ostracoda

Introduction

Based on oxygen isotope data at DSDP Site 588 and vertical changes in diatom frequencies at Site 572, three periods of significant climatic warming were noted by Barron and Baldauf (1990) during the Miocene in the North Pacific region. One of these climatic optima, which lasted from ca. 16.5 to 15 Ma, has been referred to as the "mid-Neogene climatic optimum" of Tsuchi (1986), "tropical spike" of Itoigawa (1989), or "climatic optimum 1" of Barron and Baldauf (1990). This interval is characterized by relatively low oxygen-isotope values for benthic foraminifers from deep seas of the equatorial Pacific Ocean (e.g., Savin *et al.*, 1981 ; Woodruff *et al.*, 1981 ; Woodruff and Savin, 1989 ; Kennett, 1986). During this interval, the tropical to subtropical shallow-water Kurosedani-Kadonosawa molluscan fauna

spread up to southern Hokkaido in Japan (e.g., Oyama, 1950 ; Chinzei, 1986 ; Tsuchi, 1986 ; Itoigawa, 1989 ; Itoigawa and Yamanoi, 1990). Mangrove swamps also developed were especially on the proto-Japan Sea side at that time (Oyama, 1950 ; Yamanoi *et al.*, 1980 ; Itoigawa and Yamanoi, 1990). After that, major middle Miocene cooling began 14.9 Ma and continued to 12.4 Ma, particularly at high latitudes (Savin *et al.*, 1981 ; Woodruff *et al.*, 1981). During this interval, oxygen isotope values for benthic foraminifers increased by more than 1.0‰ (Savin *et al.*, 1981 ; Woodruff *et al.*, 1981 ; Woodruff and Savin, 1989) and the cool-temperate water Shiobara-Yama molluscan fauna dominated in northeastern Japan (Chinzei and Iwasaki, 1967 ; Iwasaki, 1970). Such marine climatic cooling was caused globally by the formation of the East Antarctic ice sheet (Woodruff *et al.*, 1981 ; Kennett, 1986) and locally by collision of Southwest Japan and the

Izu-Bonin Arc (Nishimura, 1994). Recently Miller et al. (1991), Wright and Miller (1992) and Wright et al. (1992) proposed global Oligocene-Miocene oxygen isotope zones. Their syntheses suggest that glacial episodes have repeatedly punctuated post-Eocene climatic history.

Many workers have studied the relationships between ostracode faunas and Plio-Pleistocene climatic fluctuations in Japan (e.g., Ishizaki et al., 1993; Cronin et al., 1994, Ozawa, 1996). However, Miocene ostracode faunas have been studied only locally in Japan (Ishizaki, 1963, 1966; Nohara, 1987; Yajima, 1988, 1992; Irizuki, 1994; Irizuki and Matsubara, 1994, 1995; Ishizaki et al., 1996), and only a few attempts have so far been made at revealing faunal sequences in relation to Early to Middle Miocene marine climatic history. Irizuki and Matsubara (1994, 1995) analyzed in detail vertical changes of ostracode faunas from the Lower to Middle Miocene Kadonosawa and Middle Miocene Suenomatsuyama Formations in the Ninohe area, northeastern Japan. They recognized that circumpolar and cryophilic species first appeared at the base of the *Denticulopsis praelauta* Zone (the middle part of the Kadonosawa Formation). In addition, they mentioned that circumpolar and cryophilic ostracodes commonly continued to occur up to the lower part of the Suenomatsuyama Formation (the upper part of the *Denticulopsis praelauta* Zone) and warm-water species in turn increased upward in the section. The interval represented by the dominance of circumpolar and cryophilic ostracodes (ca. 25-60%) in the Ninohe area is chronologically correlative with the Miocene isotope 2 event, which is defined as located between chronozones C5Cn and C5Br (ca. 16 Ma) (Miller et al., 1991). The Miocene isotope 2 event is recorded not only by benthic $\delta^{18}O$ at worldwide ODP and DSDP sites but also by planktonic $\delta^{18}O$ in the western equatorial Indian Ocean (e.g., Woodruff et al., 1981; Woodruff and Savin, 1989; Vincent et al., 1985; Kennett, 1986). Thus circumpolar and cryophilic ostracodes possibly spread south during the intervals of Miocene isotope events.

Continuous marine Middle to Upper Miocene sedimentary sequences composing the Arakawa Group are distributed in the Karasuyama area. Many workers are involved in investigations of various groups of microfossils from the same samples, and radioactive dating of intercalated tuff layers and sedimentology of the Arakawa Group. The Kobana Formation, composing the lowest part of the Arakawa Group, yields well-preserved calcareous fossils in abundance, including ostracodes which provided material for our studies. The purpose of this paper is to discuss quantitatively ostracode faunal sequences in the lower to middle part of the Kobana Formation for the first time, with reference to global marine climatic cooling (Miocene isotope events) after the mid-Neogene climatic optimum.

Geologic outline of the Karasuyama area

The Karasuyama area lies about 25 km northeast of Utsunomiya City, Tochigi Prefecture, Central Japan and is on the west side of the Yamizo Mountains of the Jurassic accretionary complex (Figure 1). The geology of this district has been investigated by Kawada (1948, 1949, 1953) and
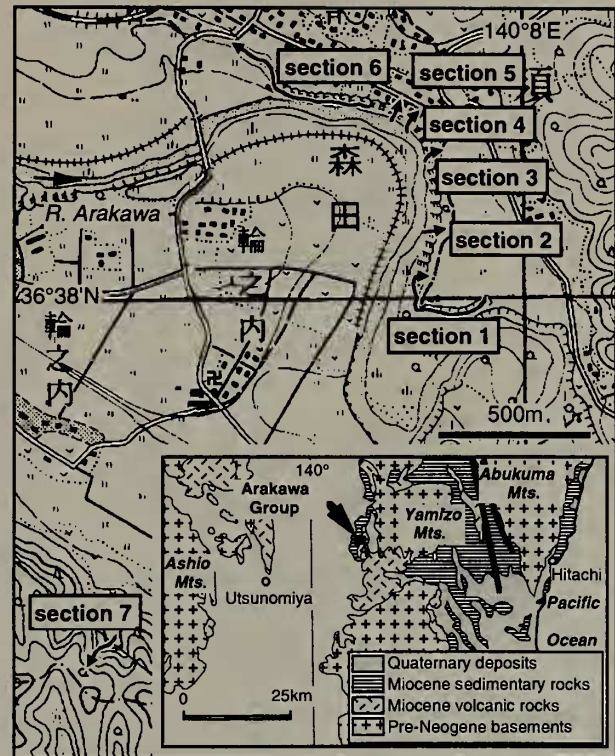

Figure 1. Geologic sketch map with the study area and topographic map showing locations of sections of the Kobana Formation measured along or near the Arakawa River (a part of topographic map "Karasuyama", 1 : 25,000 scale, Geographical Survey Institute of Japan).

Sakai (1986). The Miocene distributed around the Karasuyama area comprises two groups: the Nakagawa and Arakawa (Figure 2). The Nakagawa Group consists mainly of pyroclastic rocks and comprises four formations: the Ichiba (conglomerate), the Motokozawa (conglomerate, sandstone, siltstone, tuff and lignite seam), the Yamanouchi (basaltic to andesitic volcaniclastic deposits and lava) and the Motegi (sandstone, siltstone, pumice tuff and andesitic to dacitic lava) in ascending order (Kawada, 1953; Takahashi and Hoshi, 1995; Hoshi and Takahashi, 1996a). The Motegi and Motokozawa Formations are dated at 16.7±0.9 Ma and 18.6±1.3 Ma by the fission track method, respectively (Takahashi and Hoshi, 1995, 1996; Hoshi and Takahashi, 1996b). The Arakawa Group unconformably overlies the Nakagawa Group. It consists of marine clastic rocks with many intercalated felsic tuff layers and comprises four formations: the Kobana (basal conglomerate, calcareous sandstone, siltstone and tuff), the Ogane (sandstone, siltstone and hard shale), the Tanokura (diatomaceous mudstone), and the Irieno (muddy sandstone) in ascending order (Figure 2). Both groups are covered unconformably with the Quaternary Kawasaki Group (gravel, sand and mud). Reported from the Arakawa Group have been various groups of marine fossils: molluscs by Kanno (1961) and Hirayama (1954, 1967, 1981); radiolarians by Sakai (1986) and Sugie (1993); diatoms by Sakai (1986); planktonic foraminifers by Sakai (1986) and
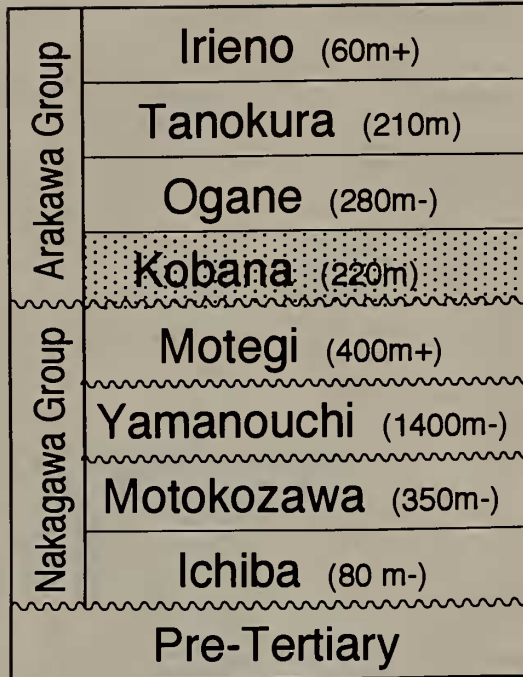
Figure 2. Stratigraphic division of the Neogene sequence of the Motegi and Karasuyama areas modified from Takahashi and Hoshi (1996).

Usami et al. (1995, 1996). The lower to middle part of the Kobana Formation is composed of basal conglomerate, very coarse- to medium-grained calcareous sandstone including large quantities of molluscan fossils, fine-grained sandstone, sandy siltstone, mudstone, and silty sandstone, in ascending order (Figure 3). The middle to upper part is composed mainly of sandy siltstone to silty sandstone with many intercalated felsic tuff layers (Kb 10 to Kb 30 of Sakai, 1986) and is conformably overlain by sandy siltstone of the Ogane Formation. Hirayama (1954, 1967, 1981) reported such subtropical molluscan fossils as *Chlamys arakawai* (Nomura), *Nipponopecten akihoensis* (Matsumoto) and *Siratoria siratoriensis* (Otuka) from the Kobana Formation. Some of them are constituents of the Kadonosawa Fauna, which represents the Early to Middle Miocene tropical to subtropical molluscan fauna. Recently, Tanaka and Takahashi (1997) determined the last occurrence horizon of *Sphenolithus heteromorphus* Deflandre between Kb 2 and Kb 3 tuff layers in the lower part of the Kobana Formation and that of *Cyclicargolithus floridanus* (Roth and Hay) Bukry in the lowermost part of the overlying Ogane Formation. Thus the Kobana Formation ranges over the calcareous nannofossil Zones CN4 to CN5a of Okada and Bukry (1980). Kb 1 and Kb 23 tuff layers are dated at 14.27 ± 0.33 Ma or 14.28 ± 0.33 Ma and 12.40 ± 0.28 Ma or 12.37 ± 0.28 Ma by the K-Ar method, respectively (Takahashi unpub. data). A sedimen-

tation rate estimated by the chronologic controls implies that the studied interval ranges in age from about 13 to 14.5 Ma (Figure 4).

Materials and laboratory procedures

For studies of several kinds of microfossil groups, about 120 samples were collected from the Kobana Formation in ten measured sections exposed along or around the Arakawa River in Minaminasu-machi (Figure 1). A total of 42 samples obtained from the lower to middle part of the Kobana Formation were selected for examining vertical changes of ostracode faunas (Figure 3). The upper part of the Kobana Formation (tuffaceous silty sandstone with many intercalated tuff layers) contains too few fossil ostracodes to perform quantitative analyses. One hundred and sixty grams of dried sediment were treated with a saturated sodium sulfate solution and naphtha for rock maceration (Maiya and Inoue, 1973), washed through a 200 mesh sieve screen (75 μm), and dried again. These procedures were repeated until the whole sediment sample disintegrated. Samples containing abundant ostracode specimens were divided by a sample splitter into workable aliquot parts, each with around 200 specimens. The ostracode number refers to the minimum number of individuals as determined by adding larger numbers of either of the valves to the carapaces, picked from fractions coarser than 125 μm (115 mesh).

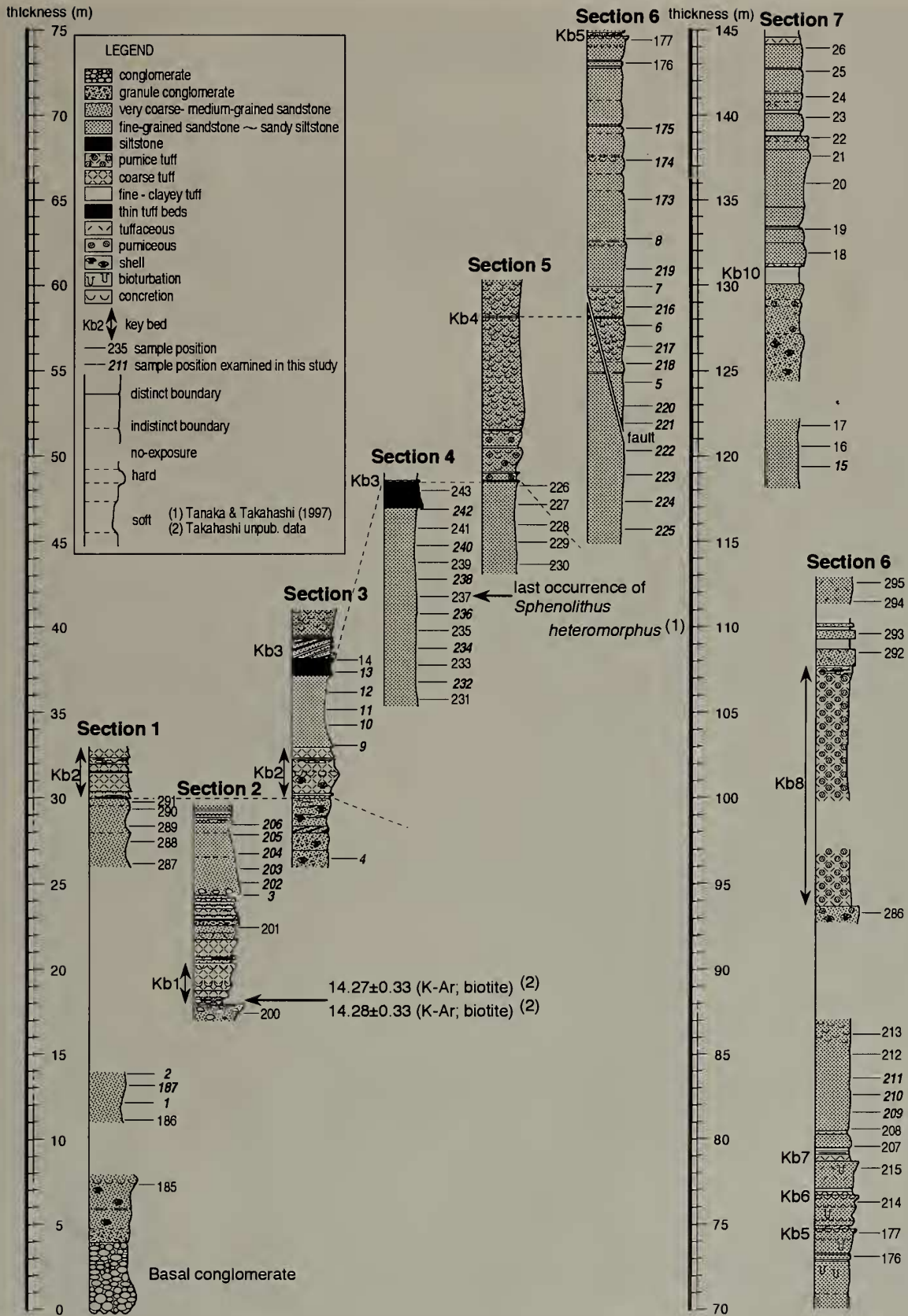### Analyses of ostracode faunas

One hundred and forty-nine species were identified from 42 samples obtained from the lower to middle part of the Kobana Formation. Figures 5 and 6 illustrate selected species from the Kobana Formation.

Only those species which were represented by three or more individuals in one or more samples were selected for further multivariate examination (Appendix I). To reveal faunal sequences of ostracodes quantitatively, the data on stratigraphic distributions of the selected 76 species by 42 samples were subjected to two kinds of multivariate analyses: Q-mode cluster and principal components analyses. The number of species, species diversity, equitability and individual number per 10 g sediment of ostracodes were selected to represent their faunal structure.

Q-mode cluster analysis

Q-mode cluster analysis using the weighted pair group arithmetic average method was carried out based on the overlap index of Horn (1966) to recognize biotopes of fossil ostracodes. This procedure grouped 42 samples into five clusters (biotopes) (A to E) (Figure 7). Table 1 summarizes dominant and subordinate ostracodes characterizing each biotope. Biotopes A to E are positioned upward in the sequence, with biotope D recurring in the uppermost part

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Figure 3. Columnar sections of the Kobana Formation in the Karasuyama area. Bold and italic numbers show samples used in this study.

thickness (m)

LEGEND

conglomerate
granule conglomerate
very coarse- medium-grained sandstone
fine-grained sandstone ~ sandy siltstone
siltstone
pumice tuff
coarse tuff
fine - clayey tuff
thin tuff beds
tuffaceous
pumiceous
shell
bioturbation
concretion

Kb2 key bed

235 sample position
211 sample position examined in this study

distinct boundary

indistinct boundary

no-exposure

hard

soft (1) Tanaka & Takahashi (1997)
(2) Takahashi unpub. data

Section 6 thickness (m) **Section 7**

Kb5 — 177
— 176
— 175
— 174
— 173
— 8
— 219
— 7
— 216
— 6
— 217
— 218
— 5
— 220
— 221
fault — 222
— 223
— 224
— 225

— 26
— 25
— 24
— 23
— 22
— 21
— 20
— 19
— 18

Kb10 Kb4

— 17
— 16
— 15

Section 5

— 243
— 242
— 241
— 240
— 239
— 238
— 237
— 236
— 235
— 234
— 233
— 232
— 231

— 226
— 227
— 228
— 229
— 230

last occurrence of
Sphenolithus
heteromorphus (1)

Section 4

Kb3

Section 3

Kb3

— 14
— 13
— 12
— 11
— 10
— 9

Section 1

Kb2

Section 2

Kb2

— 291
— 290
— 289
— 288
— 287

— 206
— 205
— 204
— 203
— 202
— 3

— 4

— 201

Kb1 14.27±0.33 (K-Ar; biotite) (2)
14.28±0.33 (K-Ar; biotite) (2)
— 200

— 2
— 187
— 1
— 186

— 185

Basal conglomerate

Section 6

— 295
— 294
— 293
— 292

Kb8

— 286

— 213
— 212
— 211
— 210
— 209
— 208
Kb7 — 207
— 215
Kb6 — 214
Kb5 — 177
— 176

(sample no. 15) of the sequence. It is notable that these biotopes are separated by major tuff beds. Figure 8 shows the stratigraphic position of the five biotopes and percentages of 19 taxa dominating each biotope.

Faunal structure

The faunal structure of ostracode assemblages is determined by the following four indices : the number of species, species diversity ($H(S)$), equitability ($Eq.$) and individual number per 10 g sediment. Species diversity can be expressed by the Shannon-Wiener formula which is independent of sample size : Diversity ($H(S)$)$= -\Sigma p_i \ln p_i$, where p_i is the proportion of the i-th species in a sample. This index has been often used in paleoecological studies. Equitability was also calculated by using the equation of Buzas and Gibson (1969) : Equitability ($Eq.$)$= e^{H(S)}/S$, S means the number of species. Maximum and minimum values of the number of species, species diversity and equitability are 61 (sample no. 5) and 22 (sample no. 232), 3.557 (sample no. 221) and 2.628 (sample no. 211), and 0.756 (sample no. 12) and 0.416 (sample no. 211), respectively. Species diversity is generally high in biotope D (average no. = 3.347), moderate in biotopes A (2.857), B (2.945) and C (3.029), and low in biotope E (2.772), depending on the number of species rather than equitability values (Figure 9).

Sample nos. 2, 3, and 216 contain more than 200 individuals per 10 g sediment. Sample no. 232 contains the fewest, 7.3 per 10 g. Average numbers are lowest in biotope C (ca. 16.2) and highest in biotope D (ca. 106) (Figure 9).

Q-mode principal components analysis

Q-mode principal components analysis was carried out to obtain clues to the intersample relationships and identify end members (samples having extreme properties). The correlation coefficient, however, may be considered inappropriate as a measure of similarity between samples (Davis, 1986) because our data set (percentage expression) will not be normally distributed. Thus the proportional similarity (cos θ) was used in this study : $\cos \theta_{ij} = \Sigma_{k=1}^{m} X_{ik} X_{jk} / (\Sigma_{k=1}^{m} X_{ik}^2 \Sigma_{k=1}^{m} X_{jk}^2)^{1/2}$, where x_{ik} and x_{jk} are the proportions of the k-th species in samples x_i and x_j. Calculated eigenvalues show that the first four components explain about 83% of the total variance (Table 2). Subsequently component scores were calculated to figure out the degree to which individual ostracode species contribute to each of the first four components (Appendix I). Figure 9 shows the stratigraphic distribution of
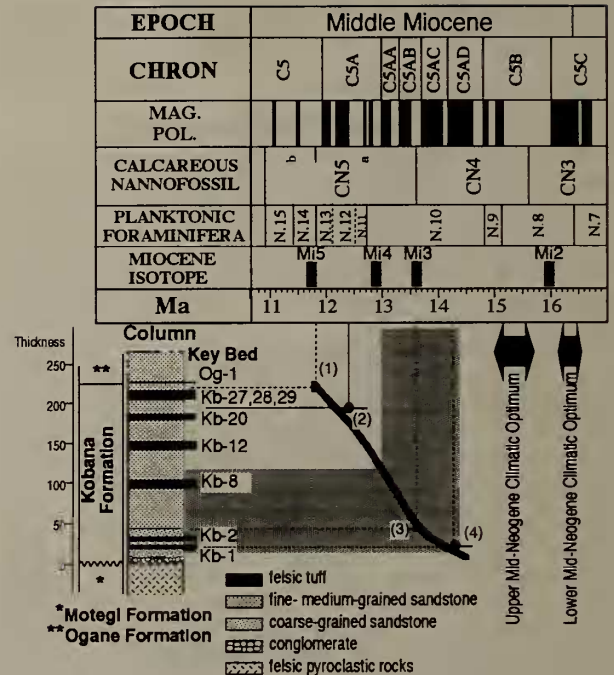

Figure 4. Geologic age and sedimentation rate of the Kobana Formation. The chronology and Miocene isotope events are based on Berggren et al. (1995) and Miller et al. (1991), respectively. (1) and (3) show the CN5a/CN5b and CN4/CN5a boundaries of calcareous nannofossil zones of Okada and Bukry (1980) as determined by Tanaka and Takahashi (1997). (2) and (4) mean K-Ar ages by Takahashi (unpub. data). Shaded area shows the studied interval. The so-called mid-Neogene climatic optimum may be subdivided into two intervals (lower and upper) by the Miocene isotope 2 event.

factor loadings (correlation coefficients between initial data and components) in relation to the first four components.

The first component.—This component explains 59.5% of the total variance. *Schizocythere kishinouyei* (Kajiyama) (score$= +64.13$), *Paracytheridea neolongicaudata* Ishizaki (score$= +56.50$), *Cornucoquimba moniwensis* (Ishizaki) (score$= +55.46$), *Cornucoquimba saitoi* (Ishizaki) (score$= +34.26$) and *Neonesidea* cf. e*legans* (Brady) (score$= +29.94$) contribute greatly to this component. They are

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Figure 5. Selected ostracode species from the Kobana Formation (part 1). All micrographs are of adult specimens. RV=right valve ; LV=left valve ; RC=right lateral view of carapace. **1** : *Neonesidea* cf. *elegans* (Brady), female RV, Loc. no. 7, ×43.7. **2** : *Argilloecia hanaii* Ishizaki, RV, Loc. no. 8, ×58.5. **3** : *Krithe antisawanensis* Ishizaki, RC, Loc. no. 217, ×58.5. **4** : *Callistocythere kotorai* Ishizaki, RV, Loc. no. 4, ×90. **5** : *Callistocythere subsetanensis* Ishizaki, RV, Loc. no. 1, ×90. **6** : *Cythere omotenipponica* Hanai, female RV, Loc. no. 7, ×90. **7** : *Schizocythere kishinouyei* (Kajiyama), female RV, Loc. no. 219, ×90. **8** : *Palmenella limicola* (Norman), RV, Loc. no. 5, ×90. **9** : *Hemicythere kitanipponica* (Tabuki), female RV, Loc. no. 223, ×58.5. **10** : *Hemicythere ochotensis* Schornikov, female LV, Loc. no. 3, ×58.5. **11** : *Aurila* sp., male RV, Loc. no. 219, ×58.5. **12** : *Pseudoaurila okumurai* (Yajima), male RV, Loc. no. 219, ×58.5. **13** : *Pseudoaurila* sp., RV, Loc. no. 218, ×58.5. **14** : *Finmarchinella hanaii* Okada, female LV, Loc. no. 2, ×90. **15** : *Finmarchinella japonica* (Ishizaki), female RV, Loc. no. 221, ×90. **16** : *Laperousecythere* aff. *robusta* (Tabuki), female RV, Loc. no. 211, ×58.5. **17** : *Laperousecythere sendaiensis* (Ishizaki, Fujiwara and Irizuki), female RV, Loc. no. 15, ×58.5. **18** : *Laperousecythere* sp., female RV, Loc. no. 219, ×58.5.
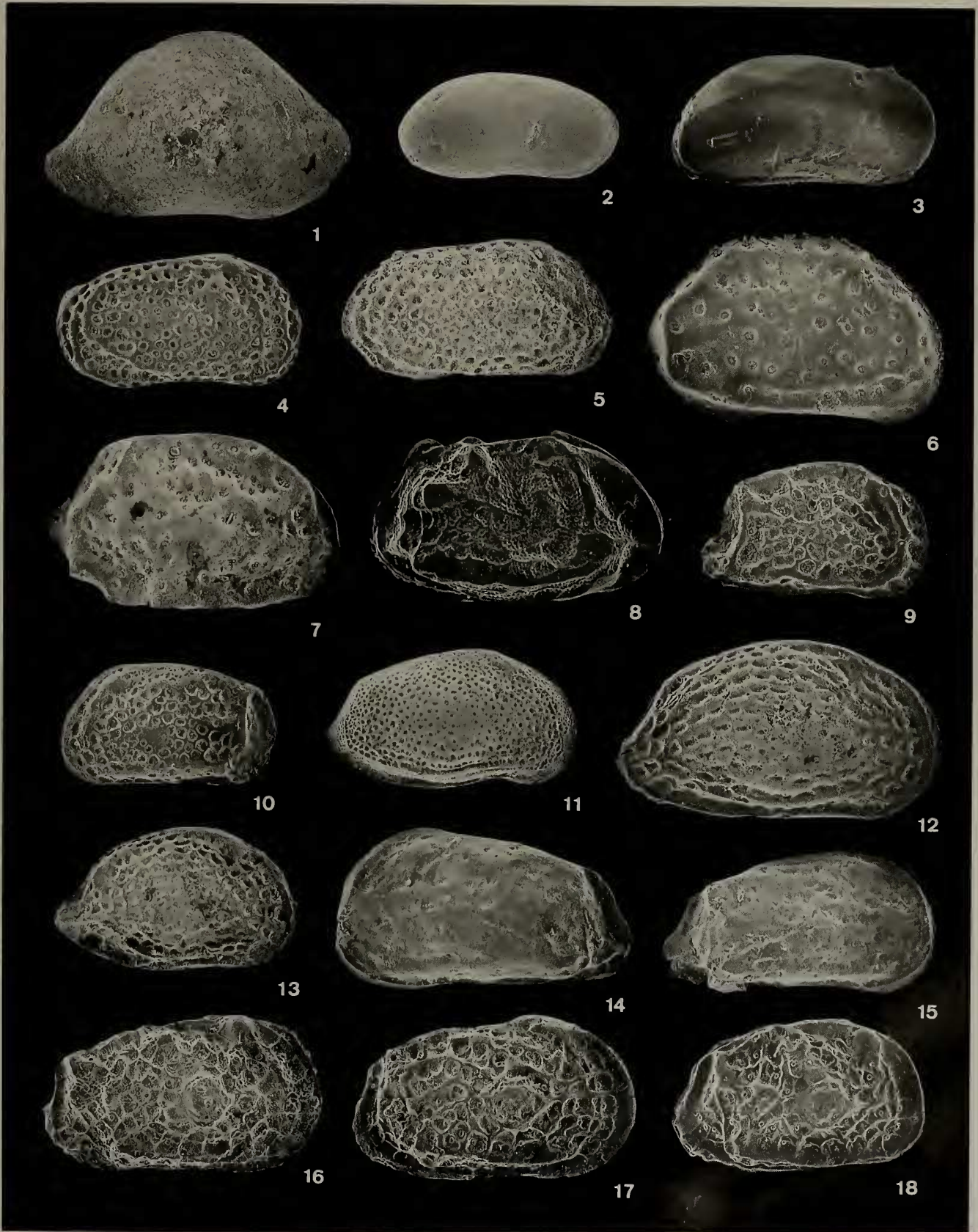
contained in abundance in most of the samples examined. The first component scores are related to the abundance of ostracode species. Most of those ostracodes are intertidal to upper sublittoral species and live predominantly in subtropical to warm-temperate areas around Japan, influenced by the Kuroshio Warm Current (e.g., Hanai et al., 1977; Tsukagoshi and Ikeya, 1987; Ikeya and Cronin, 1993; Zhou, 1995). They also have often been recorded from Neogene deposits around Japan, Korea and Formosa (e.g., Hanai et al., 1977; Hu, 1984, 1986; Huh and Paik, 1992a, b, 1993; Huh, 1994). Vertical fluctuations of the first factor loading are concordant with those of the number of species and species diversity. The second to fourth components can be interpreted by not only values of corresponding component scores but also by the ratio of scores with regard to the first to each of the remaining components.

The second component.—This component explains 9.87% of the total variance. *Laperousecythere* sp. (score= +16.452), *Krithe antisawanensis* (score= +16.114), *Laperousecythere sendaiensis* (Ishizaki, Fujiwara and Irizuki) (score= +15.849), *Palmenella limicola* (Norman) (score= +13.106), *Falsobuntonia taiwanica* Malz (score= +12.743) and *Hirsutocythere*? sp. 1 (score= +11.657) have high positive scores of the second component and also high ratios of the first to second component scores. *Neonesidea* cf. *elegans* (score= −23.714), *P. neolongicaudata* (score= −21.933), *C. saitoi* (score= −17.868) and *Cythere omotenipponica* Hanai (score= −11.830) have high negative scores of the second component. *Loxoconcha* sp. (c1 : c2 ratio= −1.779), *Schizocythere* sp. (ratio= −1.663), *Finmarchinella* spp. (ratio= −1.098- −1.201) and *Hemicytherura* cf. *clathrata* (Sars) (ratio= −1.611), have high negative ratios of the first to second component scores. *Krithe antisawanensis*, *P. limicola* and *F. taiwanica* are extant and live predominantly in the lower sublittoral to upper bathyal around Japan (more than 150 m in depth) (Ishizaki, 1977, 1981; Ikeya and Suzuki, 1992; Zhou and Ikeya, 1992; Zhou, 1995) and were reported from black mudstone of the Lower to Middle Miocene Kadonosawa Formation (Irizuki and Matsubara, 1994). On the other hand, species with high negative component scores and ratios are abundant in intertidal to upper sublittoral areas (e.g., Hanai et al., 1977; Ikeya and Itoh, 1991; Zhou, 1995). Moreover, vertical fluctuations of the second factor loading are in inverse relation with those of individual numbers of ostracodes in 10 g sediment. Ostracodes are generally more abundant in the sublittoral than in the bathyal.

Thus the second component is interpreted as a relative water depth (positive=deep; negative=shallow).

The third component.—This component explains 8.51% of the total variance. *Laperousecythere sendaiensis* (score= +39.021), *Laperousecythere* sp. (score= +20.645), *Aurila* sp. (score= +18.051) have high positive scores. *Laperousecythere* aff. *robusta* (Tabuki) (c1 : c3 ratio= +2.181), *Munseyella hokkaidoana* Hanai (ratio= +1.433) and *Acanthocythereis munechikai* Ishizaki (ratio= +1.193) have high positive ratios of the first to third component scores. *Schizocythere kishinouyei* (score= −17.546), *P. neolongicaudata* (score= −15.317) have high negative scores. *Hirsutocythere*? sp. 1 (c1 : c3 ratio= −0.876), *Semicytherura* sp. 1 (ratio= −0.779), *Palmoconcha* sp. (ratio= −0.758) and *Hemicytherura* cf. *clathrata* (ratio= −0.727) have high negative ratios of the first to third component scores. It is rather difficult to interpret the significance of this component since *L. sendaiensis*, *Laperousecythere* sp. and *Aurila* sp. are extinct species. However, other species having high positive values seem to have lived in offshore open shelf environments. On the other hand, species having high negative values dominate nearshore sandy facies. *Hirsutocythere*? sp. 1 and *Palmoconcha* sp. were reported from the biotope B in the lower part of the Kadonosawa Formation, suggesting an enclosed muddy bay facies (Irizuki and Matsubara, 1994). Hence this component probably suggests relatively nearshore (negative) versus offshore open-shelf (positive) environments.

The fourth component.—This component explains 6.81% of the total variance. *Aurila* sp. (score= +17.92), *Neonesidea* cf. *elegans* (score= +6.223) and *C. moniwensis* (score= +6.111) have high positive scores. *Trachyleberis* cf. *mizunamiensis* Yajima (c1 : c4 ratio= +1.087), *Krithe japonica* Ishizaki (ratio= +1.058) have high positive ratios of the first to fourth component scores. *Laperousecythere sendaiensis* (score= −30.375), *P. neolongicaudata* (score= −18.066), *S. kishinouyei* (score= −14.52) have high negative scores. *Laperousecythere* aff. *robusta* (c1 : c4 ratio= −2.061), *L. sendaiensis* (ratio= −1.863), *M. hokkaidoana* (ratio= −1.313), *Hemicytherura* cf. *clathrata* (ratio= −1.205) and *Finmarchinella* spp. (ratio= −0.767- −0.993) have high negative ratios of the first to fourth component scores. *Neonesidea* cf. *elegans* is comparable to *N. elegans* reported from continental shelves off eastern and southeastern China (Whatley and Zhao, 1988). *Trachyleberis mizunamiensis* was reported from the "Shukunohora Sandstone" of the Akeyo Formation

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Figure 6. Selected ostracode species from the Kobana Formation (part 2). All micrographs are of adult specimens. **1**: *Cornucoquimba moniwensis* (Ishizaki), female RV, Loc. no. 219, ×58.5. **2**: *Cornucoquimba saitoi* (Ishizaki), male? RV, Loc. no. 8, ×90. **3**: *Cornucoquimba kagitoriensis* Ishizaki, Fujiwara and Irizuki, female RV, Loc. no. 219, ×58.5. **4**: *Hermanites*? *posterocostatus* Ishizaki, male RC, Loc. no. 8, ×58.5. **5**: *Coquimba* sp. 1, RV, Loc. no. 1, ×58.5. **6**: *Acanthocythereis munechikai* Ishizaki, female RC, Loc. no. 210, ×58.5. **7**: *Hirsutocythere*? *hanaii* Ishizaki, female RV, Loc. no. 173, ×43.7. **8**: *Abrocythereis* cf. *guangdongensis* Gou, female RV, Loc. no. 216, ×58.5. **9**: *Falsobuntonia taiwanica* Malz, female? RV, Loc. no. 220, ×58.5. **10**: *Hemicytherura* cf. *clathrata* (Sars), female RV, Loc. no. 187, ×120. **11**: *Kangarina yamaguchii* Tabuki, RV, Loc. no. 5, ×120. **12**: *Cytheropteron miurense* Hanai, RV, Loc. no. 3, ×90. **13**: *Cytheropteron postornatum* Zhao, RV, Loc. no. 234, ×90. **14**: *Cytheropteron sendaiense* Ishizaki, female RV, Loc. no. 218, ×90. **15**: *Cytheropteron* cf. *smithi* Nohara, RV, Loc. no. 5, ×120. **16**: *Cytheropteron uchioi* Hanai, female RV, Loc. no. 223, ×90. **17**: *Metacytheropteron* sp.; RV, Loc. no. 173, ×58.5. **18**: *Paracytheridea neolongicaudata* Ishizaki, RV, Loc. no. 218, ×58.5.
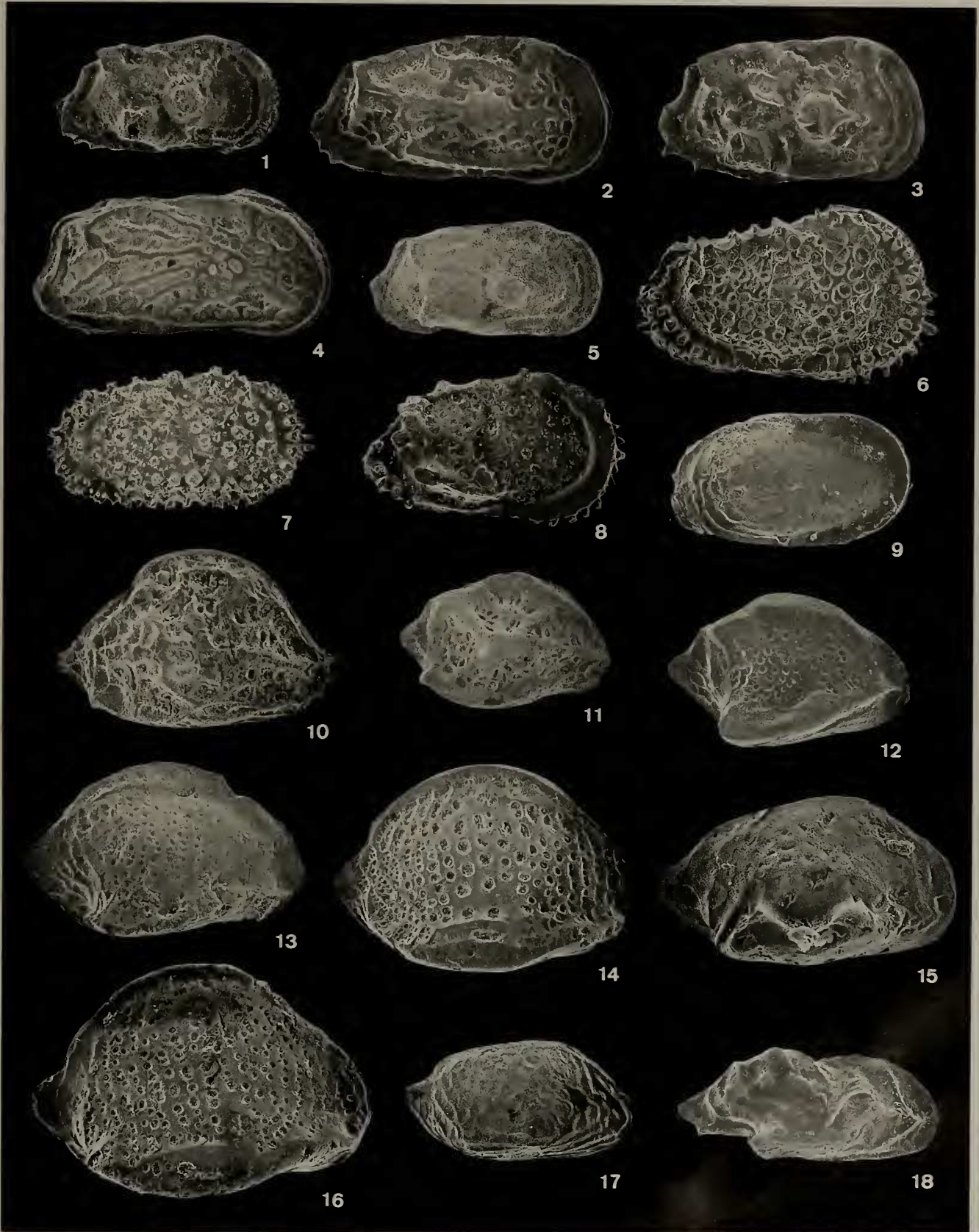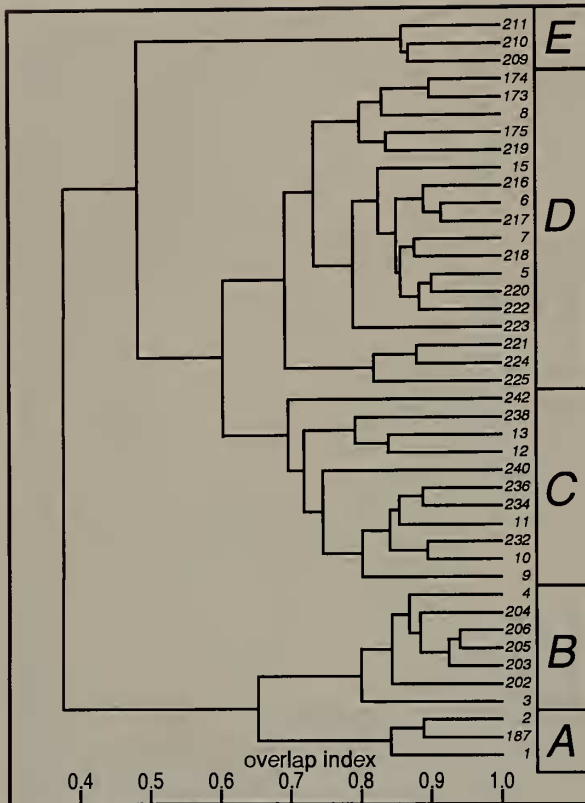
Figure 7. Dendrogram resulting from Q-mode cluster analysis based on the index of Horn's (1966) overlap. Groups A to E refer to biotopes.

which contains tropical molluscs, larger foraminifers and mangrove plants (Yajima, 1988, 1992). On the other hand *Laperousecythere* species have been reported in abundance from the lower part of the Suenomatsuyama Formation deposited during the interval of Miocene isotope 2 event (Irizuki and Matsubara, 1995) and the Upper Miocene Tsunaki Formation (ca. 8 Ma) (Ishizaki *et al.*, 1996). Both formations yield the cool-water Shiobara molluscan fauna. Only two species (*L. robusta* and *L. yahtsensis* Brouwers) are extant and living in middle sublittoral open seas of subarctic to cool-temperate zones around northern Hokkaido, northern Japan, (Itoh, 1996) and Alaska Bay (Brouwers, 1993). Other ostracodes having high negative ratios of the first to fourth component scores are equated with modern species inhabiting subarctic to mild-temperate shallow water areas or species reported from Plio-Pleistocene deposits yielding the cool-water Omma-Manganji molluscan fauna (Cronin and Ikeya, 1987). Moreover, vertical fluctuations of the fourth factor loading are inversely accordant with those of the percentage of shallow circumpolar and cryophilic species (Figure 9). Among those species are *Finmarchinella hanaii* Okada, *F. japonica* (Ishizaki), *F. nealei* Okada, *Hemicythere kitanipponica* (Tabuki), *H. ochotensis* Schornikov, *Hemicytherura* cf. *clathrata* and *Laperousecythere* aff. *robusta*. Thus the fourth component suggests water temperatures (positive=dominance of warm; negative=presence of cool shallow-water species).

Temporal changes of paleoenvironments

Quantitative analyses of faunal composition and structure of ostracodes demonstrate temporal changes of paleoenvironments after the mid-Neogene climatic optimum in the Kobana Formation.

Table 1. Summary of Q-mode cluster analysis.

Biotope	Sample	Dominant Taxa	Subordinate Taxa
A	1, 187, 2	*Pseudoaurila* spp. *Paracytheridea neolongicaudata* *Hermanites* ? *posterocostatus*	*Cornucoquimba saitoi* *Schizocythere kishinouyei* *Coquimba* sp. 1
B	3, 4, 202–206	*Paracytheridea neolongicaudata* *Neonesidea* cf. *elegans* *Schizocythere kishinouyei*	*Cornucoquimba saitoi* *Cythere omotenipponica* *Cornucoquimba moniwensis*
C	9–13, 232–242	*Schizocythere kishinouyei* *Cornucoquimba moniwensis* *Hirsutocythere* ? spp.	*Krithe antisawanensis* *Paracytheridea neolongicaudata* *Palmenella limicola*
D	5–8, 15, 216–225, 173–175	*Cornucoquimba moniwensis* *Aurila* sp. *Schizocythere kishinouyei*	*Paracytheridea neolongicaudata* *Neonesidea* cf. *elegans* *Cornucoquimba saitoi*
E	209–211	*Laperousecythere sendaiensis* *Laperousecythere* sp. *Schizocythere kishinouyei*	*Cornucoquimba moniwensis* *Laperousecythere* aff. *robusta* *Cytheropteron* sp. 2

Figure 8. Diagram showing stratigraphic positioning of biotopes and percentages of each of the 19 taxa. A to E stand for biotopes. CN 4 and CN5a are calcareous nannofossil zones of Okada and Bukry (1980) as determined by Tanaka and Takahashi (1997). For explanation of columnar section see Figure 3.
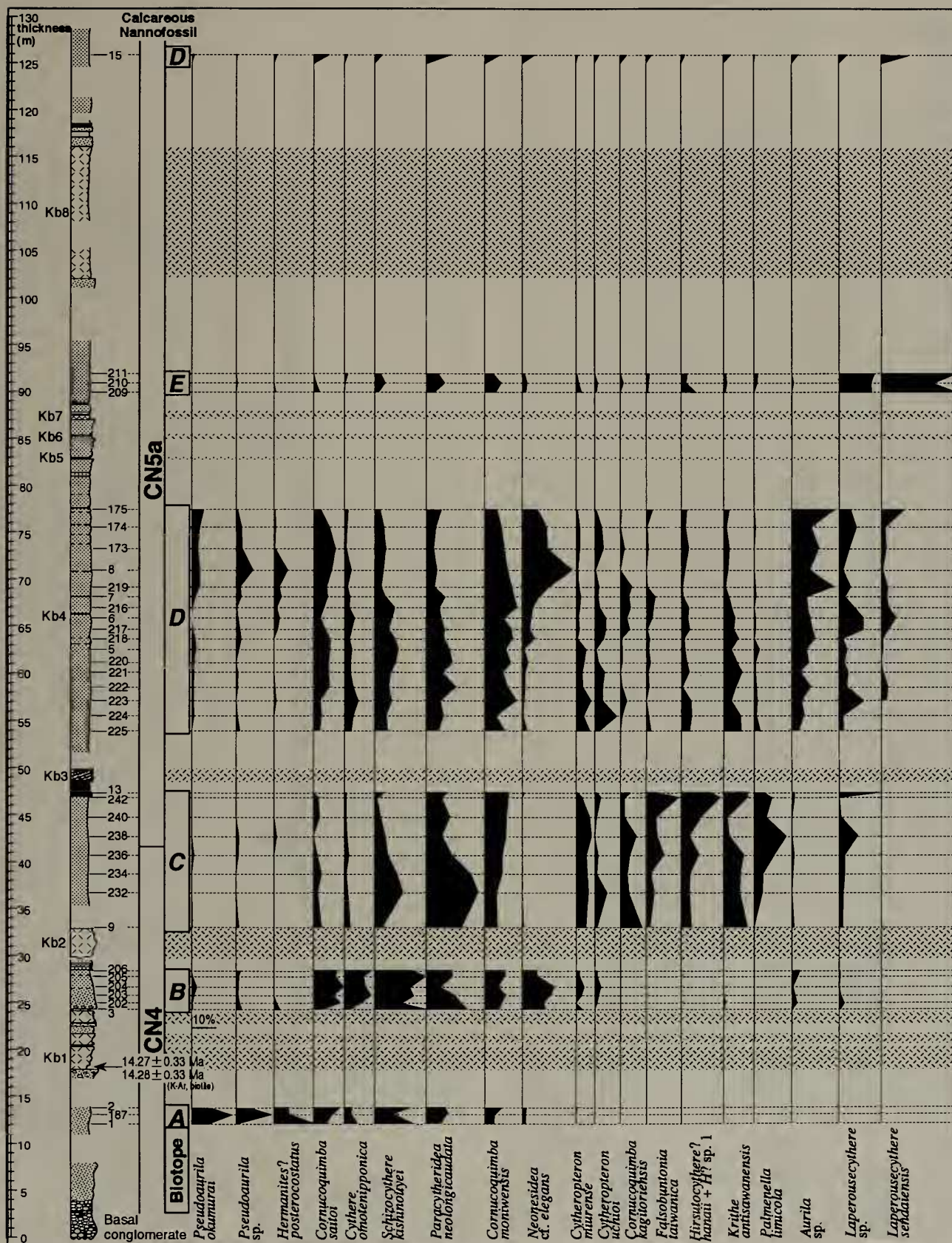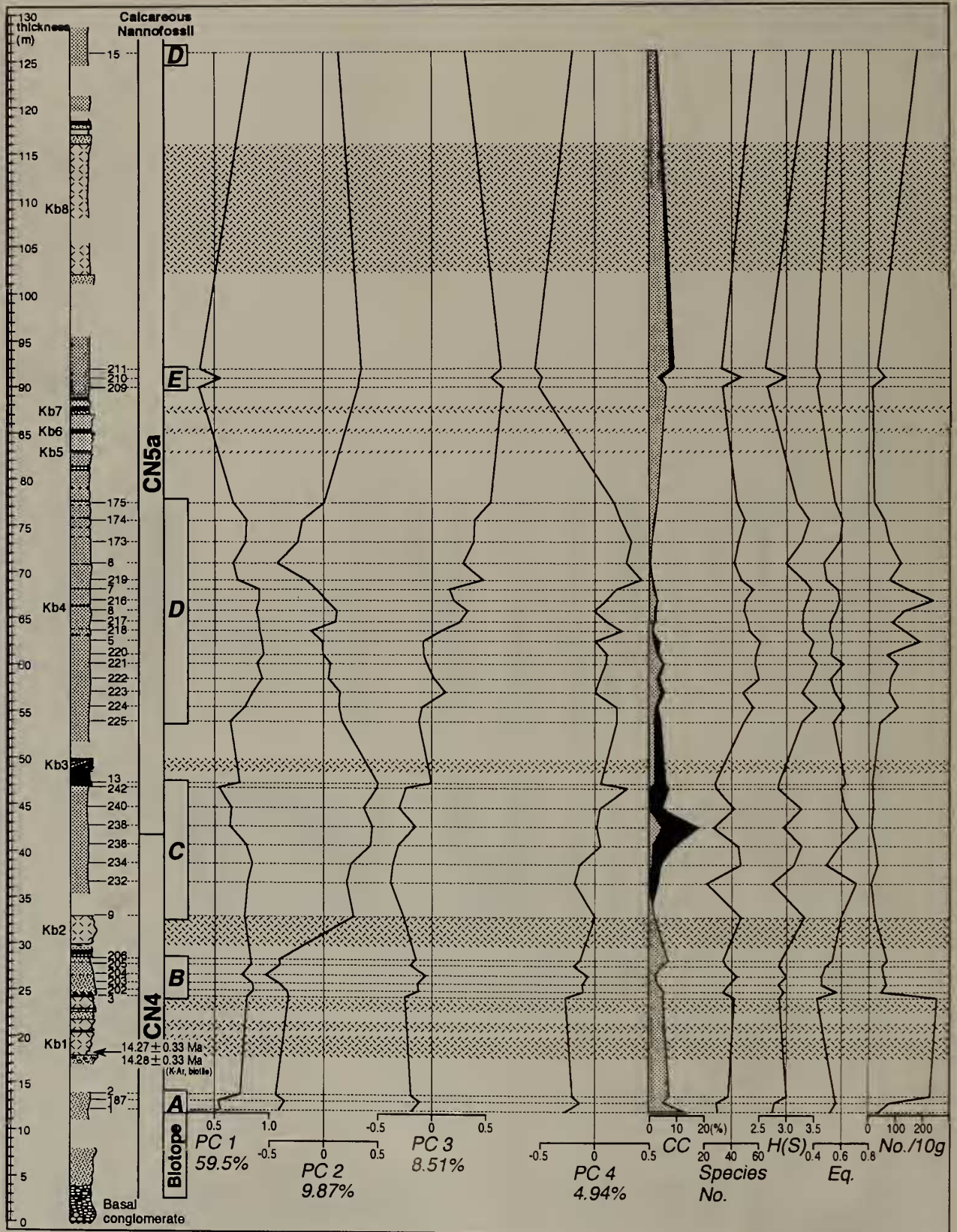
Table 2. Summary of Q-mode principal components analysis.

	Eigenvalue	Percentage	Cumulative Per.
PC 1	24.991	59.503	59.503
PC 2	4.145	9.870	69.373
PC 3	3.573	8.508	77.881
PC 4	2.073	4.937	82.818

The general pattern of ostracode faunas is shown by vertical changes in factor loadings with respect to the first component. Subtropical to warm-temperate open sublittoral ostracodes are abundant throughout the Middle Miocene Kobana Formation except for samples from the upper half of biotope C (upper bathyal species are dominant) and biotope E (cool-water ostracodes endemic to northern Japan are dominant).

Water depth

Samples in the lower part (biotopes A and B) have high negative loadings of the second component (shallow waters) and high negative third factor loadings (nearshore environments). Samples in the middle and upper parts (biotope C, the lower part of biotope D and biotope E) have high positive second factor loadings (deep waters). Such lower sublittoral to upper bathyal species as *P. limicola, K. antisawanensis, Hirsutocythere*? spp., *F. taiwanica* and *C. kagitoriensis* begin to occur in biotope C and linger on to the uppermost sample. The lowest values of individual numbers of ostracodes per 10 g in biotopes C and E are in good agreement with high positive factor loadings with respect to the second component, suggesting the prevalence of the greatest water depth during deposition of these biotopes (Figure 9). Samples in the upper part of biotope D have high negative second factor loading, and yielded large quantities of shallow-water ostracodes. However, they also commonly contain lower sublittoral to upper bathyal species (Figure 8). The third component shows that the upper part of biotope D was deposited on an open shelf. In modern offshore southwestern Japan, many intertidal and upper sublittoral species are transported downslope and are found at a depth of several hundred meters (Zhou, 1995). Thus shallow-water specimens contained in the upper part of biotope D are considered to have been displaced, resulting in large numbers of specimens and species diversity.

In this way, the second and third factor loadings show vertical changes in paleodepth during deposition of the Kobana Formation : 1) The Kobana Formation was deposited in shallow littoral to sublittoral, relatively nearshore environments during deposition of biotopes A and B ; 2) Water depth rapidly increased and upper bathyal ostracodes dominated biotope C ; 3) After that, water depth gradually began to decrease, leading to mixing of upper sublittoral and

lower sublittoral species in biotope D ; 4) Finally middle to lower sublittoral open-water species dominated biotope E.

Water temperature

Biotope A contains abundant *Pseudoaurila okumurai* (Yajima), *Pseudoaurila* sp., *Paracytheridea neolongicaudata, Hermanites*? *posterocostatus* Ishizaki, *Callistocythere subsetanensis* Ishizaki and *Coquimba* sp. 1. These species are all extinct except *P. neolongicaudata*. This fauna is very similar to the tropical to subtropical shallow-water fauna reported from Lower to Middle Miocene deposits which yield the Akeyo, Kurosedani and Kadonosawa molluscan faunas (Ishizaki, 1966 ; Yajima, 1988, 1992 ; Huh and Paik, 1992b). However, such cryophilic and circumpolar species as *Finmarchinella hanaii, F. nealei, Hemicythere kitanipponica* and *Hemicytherura* cf. *clathrata* are also included in biotope A in amounts of 5-13% (Figure 9) whereas tropical *Bairdoppilata* is absent. These species have high negative ratios of the first to fourth component scores and are included neither in Middle Miocene deposits distributed in southwestern Japan (Ishizaki, 1963, Yajima, 1988, 1992) nor in the lower part of the mid-Neogene climatic optimum (e.g., the lower part of the Kadonosawa Formation) (Irizuki and Matsubara, 1994). On the contrary, cryophilic and circumpolar species are recognized in the upper part of the mid-Neogene climatic optimum of northeastern Japan (Irizuki and Matsubara, 1994, 1995). It might be possible that Miocene counterparts of modern circumpolar-cryophilic species never experienced cold-water environments, unlike Recent ones. However, in reality, they have not been recorded from deposits in southwestern Japan during the interval of the mid-Neogene climatic optimum. They are, therefore, expected to have lived in slightly colder water, if at all, than other species in the Miocene. Thus the lower part of the Kobana Formation (biotope A) is treated as a deposit in warm shallow water, influenced by cooler coastal currents from northern areas.

In species composition biotope B is similar to the Sunakosaka and Moniwa Formations (Ishizaki, 1963, 1966), which were also deposited in the mid-Neogene climatic optimum. Biotope B also includes cryophilic and circumpolar species in abundances of 2-7%.

It is difficult to discuss bottom paleotemperature in shallow areas during deposition of biotope C because biotope C and the lower part of biotope D contain large quantities of lower sublittoral to upper bathyal ostracodes. Sample nos. 13, 238 and 242 include, however, *P. limicola, Laperousecythere* sp. and *C. kagitoriensis* in abundance (Figure 8). *Palmenella limicola* lives in the middle sublittoral in high-latitude areas of the Northern Hemisphere (Brouwers, 1993) in contrast to upper bathyal zones around Japan (e.g., Ikeya and Suzuki, 1992). Ishizaki *et al.* (1996) described *C. kagitoriensis* from the Upper Miocene Tsunaki Formation, northeastern Japan and suggested that this species increased in number with

Figure 9. Diagram showing vertical fluctuations of factor loadings with respect to the first four components, percentage of circumpolar and cryophilic species (*CC*), the number of species, species diversity (*H(S)*), equitability (*Eq.*), and individual number per 10 g sediment (*No. /10 g*). ■ and ▨ in *CC* stand for percentages of shallow circumpolar and cryophilic species and *Palmenella limicola*, respectively.

decreasing water temperatures.   The boundary between the calcareous nannoplankton Zones CN4 and CN5a is placed above sample no. 237 (between sample nos. 236 and 238) (Tanaka and Takahashi, 1997) and is chronologically correlative with the period of the Miocene isotope 3 event (Miller et al., 1991).   Thus the increase of those species possibly reflects decreased bottom-water temperatures in lower sublittoral to upper bathyal zones during the interval of the Miocene isotope 3 event.   Faunas, including circumpolar P. limicola, in these biotopes do not contain such upper bathyal circumpolar species as Acanthocythereis dunelmensis (Sars) s.l., Elofsonella cf. concinna (Jones) or Normanicythere sp., reported from the Middle Miocene Kadonosawa and Suenomatsuyama Formations, located 500 km north of the present studied area (Irizuki and Matsubara, 1994, 1995), but do contain Hirsutocythere ? hanaii, Argilloecia hanaii Ishizaki and K. antisawanensis, all of which live predominantly in lower sublittoral to upper bathyal zones of subtropical to warm-temperate areas around Japan.   Thus bottom-water temperature during deposition of both biotopes C and D of the Kobana Formation was warmer than that of the upper part of the Kadonosawa and the lower part of the Suenomatsuyama Formation.   It is noteworthy that Laperousecythere sendaiensis first occurred in the lower part of biotope D (Figure 8).

The upper part of biotope D has high negative values of the fourth factor loading (relatively warm).   Most samples in the upper part of biotope D contain relatively high ratios of shallow warm-water species (Pseudoaurila spp., Hermanites ? posterocostatus and Neonesidea cf. elegans) and such tropical to subtropical open-shelf forms as Abrocythereis cf. guangdongensis Gou, Acanthocythereis munechikai Ishizaki, Cytheropteron postornatum Zhao, Cytheropteron uchioi Hanai, Kangarina yamaguchii Tabuki, Metacytheropteron sp., Pacambocythere spp., Saida spp. and Typhlocythere spp., which live now in the East and South China Seas (Ishizaki, 1977, 1981 ; Malz and Tabuki, 1988 ; Zhao, 1988 ; Zhao and Wang, 1988 ; Zhou, 1995).   Hence bottom-water temperatures may have increased again during deposition of the upper part of biotope D.

Biotope E has the highest negative loading of the fourth factor, with the dominance of Laperousecythere spp. and the decrease of subtropical to warm-temperate water ostracodes mentioned above.   Laperousecythere sendaiensis is a principal constituent of this biotope.   It is clear that this biotope includes cooler-water species than the other biotopes.   The third component reveals that biotope E was deposited in open-shelf environments (Figure 9).   Hence it is suggested that some climatic cooling occurred even in the open shelf around the time when the boundary between biotopes D and E was settled.   This water temperature decrease appears to have been minor because cryophilic and circumpolar species amount only to less than 10% in biotope E (Figure 8).

Bottom water temperatures fluctuated during deposition of biotopes C to E.

Conclusions

The following four major results were obtained from the study of faunal changes of ostracodes from the lower to middle part of the Kobana Formation.

1.   One hundred and forty nine species of ostracodes were discriminated in the Middle Miocene Kobana Formation.   Among the dominant species are some living now in subtropical to warm-temperate sublittoral areas.

2.   Q-mode cluster analysis grouped 42 samples into five clusters (biotopes) (A to E)

3.   The second principal component shows vertical changes of water depth as follows : intertidal to middle sublittoral in the lower part ; a rapid increase of water depth (upper bathyal) in the lower middle part ; a gradual decrease of water depth (lower to middle sublittoral) from the middle to upper part.

4.   Vertical changes of bottom-water temperature during deposition of the Kobana Formation were suggested by the fourth principal component as follows : a) The lower part was influenced predominantly by subtropical shallow water, with inflowing cooler waters ; b) Fluctuations of bottom water temperature were recognized in the middle to upper part ; c) Two intervals of climatic deterioration were recognized : the first is at the horizon around the upper part of biotope C (the boundary between calcareous nannoplankton CN4 and CN5a assigned to the Miocene isotope 3 event) and the second is in the depositional interval of biotope E (the upper part of the studied section).

After the mid-Neogene climatic optimum, water temperatures fluctuated, with no rapid decrease in the Karasuyama area.

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Appendix I.   Scores with respect to the first four principal components and ratios of scores with regard to the first to each of the remaining components for 76 species selected for both Q-mode principal components and cluster analyses.

Kobana Formation	PC1	PC2	PC2/PC1	PC3	PC3/PC1	PC4	PC4/PC1
Abrocythereis cf. *guangdongensis*	1.930	0.945	0.490	−0.228	−0.118	0.476	0.247
Acanthocythereis munechikai	1.830	2.136	1.167	2.184	1.193	−2.026	−1.107
Argilloecia hanaii	7.805	2.162	0.277	−0.073	−0.009	2.627	0.337
Argilloecia toyamensis	1.815	0.565	0.311	−0.199	−0.110	0.571	0.315
Argilloecia sp. 1	1.580	−0.312	−0.198	0.237	0.150	0.949	0.600
Aurila sp.	27.201	−4.382	−0.161	18.051	0.664	17.917	0.659
Callistocythere kotorai	5.008	−2.916	−0.582	−1.588	−0.317	−1.656	−0.331
Callistocythere subsetanensis	1.392	−0.844	−0.606	−0.685	−0.492	−0.793	−0.570
Callistocythere sp.	1.084	−0.383	−0.354	−0.562	−0.519	−0.534	−0.493
Coquimba sp. 1	4.973	−4.132	−0.831	−0.986	−0.198	−1.093	−0.220
Cornucoquimba kagitoriensis	12.357	7.964	0.645	−1.444	−0.117	1.846	0.149
Cornucoquimba moniwensis	55.459	4.574	0.082	3.646	0.066	6.111	0.110
Cornucoquimba saitoi	34.260	−17.868	−0.522	1.018	0.030	−0.372	−0.011
Cornucoquimba sp.	5.209	1.239	0.238	4.073	0.782	−0.334	−0.064
Cythere omotenipponica	22.746	−11.830	−0.520	−3.388	−0.149	−4.249	−0.187
Cythere uranipponica	4.178	−1.005	−0.240	−0.908	−0.217	−0.789	−0.189
Cytheropteron miurense	17.553	6.553	0.373	−4.929	−0.281	−0.091	−0.005
Cytheropteron postornatum	1.816	1.434	0.790	−0.706	−0.389	−0.552	−0.304
Cytheropteron sendaiense	6.981	−0.179	−0.026	2.157	0.309	0.714	0.102
Cytheropteron cf. *smithi*	1.783	0.986	0.553	−1.087	−0.610	0.185	0.104

Cytheropteron uchioi	13.089	1.640	0.125	1.964	0.150	3.814	0.291
Cytheropteron sp. 1	14.939	8.304	0.556	−1.846	−0.124	−0.937	−0.063
Cytheropteron sp. 2	3.929	2.077	0.529	5.680	1.446	−3.628	−0.924
Cytheropteron sp. 3	3.894	−1.097	−0.282	−0.972	−0.250	−0.449	−0.115
Cytheropteron sp. 4	2.730	0.032	0.012	2.108	0.772	0.576	0.211
Cytheropteron sp. 5	1.695	0.073	0.043	0.063	0.037	0.759	0.448
Cytheropteron sp. 6	0.931	0.451	0.484	0.566	0.608	−0.260	−0.280
Eucythere sp. 1	0.924	0.334	0.361	0.836	0.905	−0.320	−0.346
Falsobuntonia taiwanica	12.544	12.743	1.016	−3.492	−0.278	4.548	0.363
Finmarchinella hanaii	1.372	−1.507	−1.098	−0.744	−0.543	−1.052	−0.767
Finmarchinella japonica	5.304	−0.001	0.000	−0.666	−0.126	0.213	0.040
Finmarchinella nealei	0.274	−0.329	−1.201	−0.178	−0.651	−0.272	−0.993
Hemicythere kitanipponica	7.123	−5.565	−0.781	−1.556	−0.218	−3.644	−0.512
Hemicythere ochotensis	2.403	−0.448	−0.187	−0.311	−0.129	−0.299	−0.125
Hemicytherura cf. *clathrata*	0.565	−0.910	−1.611	−0.411	−0.727	−0.681	−1.205
Hemicytherura cuneata	1.919	−0.137	−0.072	0.059	0.031	−0.030	−0.015
Hermanites ? *posterocostatus*	8.049	−7.689	−0.955	0.257	0.032	−3.235	−0.402
Hirsutocythere ? *hanaii*	14.705	9.097	0.619	1.218	0.083	−1.958	−0.133
Hirsutocythere ? sp. 1	6.563	11.657	1.776	−5.746	−0.876	4.850	0.739
Kangarina yamaguchii	1.225	0.106	0.086	−0.807	−0.659	−0.287	−0.234
Kotoracythere cf. *abnorma*	0.676	0.210	0.310	0.375	0.555	−0.195	−0.288
Krithe antisawanensis	25.462	16.114	0.633	−6.628	−0.260	5.534	0.217
Krithe japonica	5.059	3.329	0.658	−1.775	−0.351	5.350	1.058
Laperousecythere cf. *robusta*	2.828	2.932	1.037	6.166	2.181	−5.828	−2.061
Laperousecythere sendaiensis	16.307	15.849	0.972	39.021	2.393	−30.375	−1.863
Laperousecythere sp.	26.191	16.452	0.628	20.645	0.788	−9.314	−0.356
Loxoconcha nozokiensis	5.494	−2.295	−0.418	0.281	0.051	1.481	0.270
Loxoconcha pulchra	1.486	−1.099	−0.740	−0.523	−0.352	−0.338	−0.228
Loxoconcha sp.	0.285	−0.507	−1.779	−0.097	−0.339	−0.171	−0.601
Macrocypris cf. *decora*	1.955	−0.188	−0.096	−0.305	−0.156	0.031	0.016
Metacytheropteron sp.	1.098	0.248	0.225	0.965	0.879	−0.093	−0.085
Munseyella hokkaidoana	0.883	0.847	0.959	1.265	1.433	−1.159	−1.313
Munseyella japonica	1.940	−0.730	−0.376	−0.001	0.000	−0.139	−0.072
Neomonoceratina japonica	4.437	2.951	0.665	0.184	0.041	0.466	0.105
Neonesidea cf. *elegans*	29.937	−23.714	−0.792	12.147	0.406	6.223	0.208
Neonesidea sp. 1	0.510	−0.775	−1.519	0.108	0.212	0.053	0.104
Pacambocythere sp.	1.981	0.500	0.253	−0.040	−0.020	0.544	0.275
Palmenella limicola	10.957	13.106	1.196	−6.983	−0.637	1.076	0.098
Palmoconcha sp.	7.106	7.293	1.026	−5.386	−0.758	0.238	0.033
Paracypris sp. 1	0.973	−0.377	−0.388	0.999	1.027	0.744	0.765
Paracytheridea neolongicaudata	56.504	−21.933	−0.388	−15.317	−0.271	−18.066	−0.320
Pectocythere sp.	0.709	−0.729	−1.029	0.141	0.199	−0.015	−0.021
Pseudoaurila okumurai	10.638	−9.456	−0.889	1.136	0.107	−0.721	−0.068
Pseudoaurila sp.	9.398	−8.142	−0.866	0.721	0.077	0.473	0.050
Rotundracythere ? sp.	6.922	5.826	0.842	−3.467	−0.501	−0.660	−0.095
Saida sp.	0.940	0.605	0.644	0.497	0.528	−0.154	−0.164
Schizocythere kishinouyei	64.125	6.252	0.098	−17.546	−0.274	−14.520	−0.226
Schizocythere sp.	0.739	−1.229	−1.663	−0.527	−0.713	−0.904	−1.223
Sclerochilus sp. 1	2.238	−0.543	−0.243	0.578	0.258	1.479	0.661
Semicytherura henryhowei	7.822	−4.253	−0.544	−2.385	−0.305	−3.008	−0.385
Semicytherura miurensis	0.942	−1.021	−1.083	−0.341	−0.361	−0.408	−0.433
Semicytherura sp. 1	0.866	−1.067	−1.231	−0.675	−0.779	−0.986	−1.138
Trachyleberis cf. *mizunamiensis*	0.667	−0.289	−0.433	0.641	0.961	0.725	1.087
Xestoleberis hanaii	3.075	−1.877	−0.610	0.252	0.082	0.056	0.018
Xestoleberis cf. *setouchiensis*	2.644	−0.043	−0.016	−1.121	−0.424	−0.717	−0.271
Gen. et sp. indet. 1	2.310	0.487	0.211	0.001	0.000	1.215	0.526